The structural conservation of Hagia Sophia
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INTRODUCTION: THE STRUCTURAL CONSERVATION OF HISTORICAL BUILDINGS

The conservation of a historical masonry building presents very different problems from the design of a typical new one. The historical building differs structurally in many ways from the buildings for which our present analytical tools were largely developed. It carries its loads largely by compression, the masonry usually being extensively cracked where primary tensions would otherwise arise or where high local primary compressions lead to high orthogonal tensions. It already has a particular form put together in a particular manner, often in several campaigns of construction and partial reconstruction. Yet we can rarely know all we should like to know about its structure and constituent materials. And although it has demonstrated its capacities and shortcomings over many years, the demonstrations are not in the measures that we use when designing a new building and may be difficult to interpret.

HAGIA SOPHIA

Justinian's Great Church of Hagia Sophia, later the Mosque of Aya Sofya and one of the greatest buildings of all time, exemplifies these differences to the full. It is shown as it exists today, crowned by a dome more than 30 m in span, in Fig.1.1

It was built to the orders of the Emperor Justinian between 532 and 537, so that it has now stood for almost 15 centuries. Yet its central space, vaulted in one continuous sweep from west to east, remains unequalled to this day. For the first nine centuries (apart from a relatively brief interlude during the Latin occupation of what was then Constantinople) it remained the principal church of the Byzantine Empire, and then for another five it served as the principal Ottoman mosque.

Justinian was no conservationist. Paying little respect to
its century-old predecessor on the site, he had this razed to the ground after a fire and in its place he commissioned something as novel as anything built before or since. There were, of course, smaller-scale precedents for most elements of the design. They would have demonstrated (albeit within unknown limits) both the feasibility of these elements and some of their possible uses. They would also have served as stimuli to a creative imagination. But what is more significant is that they were brought together in a wholly new manner in what was really a superlative exercise in spatial geometry by men who were masters of that discipline.²

Innovation as far reaching as this does, however, run great risks. These were all the greater on account of the scale of the enterprise and Justinian's impatience to see it finished. We know from a slightly later account that construction was not uneventful: difficulties arose soon after construction of the main arches began. An early partial collapse and two further ones more than four centuries and eight centuries later are also recorded, all them being triggered off partly by earthquakes. In addition there have been numerous campaigns of consolidation or repair and another major partial reconstruction to which the records make no explicit reference. After the first collapse the dome was raised and some later campaigns have considerably affected the outward appearance. But the reconstructions and other works have preserved most of the original structure intact to this day - a unique record for a building of its size and age.

Figure 1  The structure today showing, except at the south west, the principal external additions. (Author)
What are the future prospects? Are the present strengths adequate to ensure survival for a further century or so? Or are there weaknesses that now call for intervention? If so, what should be the criteria and how should we proceed?

DESIGN, CONSTRUCTION AND PAST PERFORMANCE

To answer these questions we must first take a closer look at the structure, at its construction history and the changes subsequently undergone, and its behaviour hitherto - those demonstrations of capacities and shortcomings referred to at the outset. Its scale and complexity and the inaccessibility of most of the working masonry behind facings of marble, mosaic or rendering make this difficult. But nothing can hide the very marked departures from what could be presumed to have been the original setting out. Once it was demonstrated that they were indeed true deformations they provided invaluable clues to set alongside the documentary record.

Working from both existing survey data and fresh observation and measurement and concentrating first on the main arches and their supporting piers, it was possible to trace the growth of their deformations and by doing so to learn more about the early difficulties, the measures taken to overcome them, the reasons for the recorded collapses and the limits of the recorded partial reconstructions. In a similar way, but testing the conclusions now by limited probing behind the present renderings, it was also

Figure 2 The original primary structural system with the vaults partly cut-away and the reconstructed section of the main west arch shown stippled. (Author)
possible to identify and roughly date the unrecorded further partial reconstruction.³

However ideas evolved, the final design stemmed from the decision to adopt a novel main vaulting system consisting of a central dome abutted by semidomes of the same diameter at east and west. This called for different provisions to carry the dome and resist its thrusts at east and west and at north and south and led to the primary support system seen in Fig.2. The support at east and west was the more novel, with the thrusts absorbed initially by the semidomes. But it was the support at north and south that proved troublesome, partly on account of a requirement for galleries over the side aisles as in the previous church. The closest precedent for it was to be found in the Basilica Nova in Rome. There, with no galleries, the main piers could be very substantially connected to others alongside them across the aisles. In Hagia Sophia the main piers were likewise supplemented by buttress piers across the aisles and they were similarly proportioned at ground level. But only very shallow interconnections were possible over the aisles without unduly interrupting their continuity or unduly raising the gallery floor and, above the gallery roof, there were initially only parallel pairs of arches carrying low walls spanned by a barrel vault. These interconnections were all the weaker because they were constructed of brickwork with wide mortar joints and were subjected to heavy load before the mortar had reached full strength. A further weakness was introduced by a considerable reduction in the cross section of the main piers at gallery level from that at ground level.

As a result of these weaknesses the supports began to yield alarmingly even before the main east and west arches had been completed. To slow down their yielding, bracing arches of cut stone carried on projections from the piers were hurriedly constructed across both aisles and galleries and the walls above were extended upwards with further barrel vaults spanning between them (Fig.3). Work then proceeded to completion, though the dome had to be set on a base that was no longer circular as intended and on arches that were already deformed, particularly the eastern one. As far as can be seen it was generally similar to the present dome except that it had a lower profile, so that its outward thrusts would have been about twice as great.

The first partial collapse was primarily a collapse of the central part of the main eastern arch. That part of the dome which rested on the collapsed section also fell, but the rest remained standing, "a wonder to behold" in the words of the contemporary account of Silentarius. It is notable that it followed one of several earthquakes in the preceeding years but that it did not occur until 5 months after the last of them while unspecified remedial work was in progress. The state after the last earthquake was probably similar to that observed recently in the Holy Trinity in Budva and the Metropolis in Mistra.⁴
Over the next 4 years the entire dome was rebuilt to a higher profile after reconstruction of the fallen part of the arch and some addition to the faces of the main north and south arches to reduce the excess of the north-south over the east-west diameter. There were also some additions to the dome base.

The second and third collapses likewise involved primarily the arches - first the main western arch then for the second time the main eastern one. Again they led to the fall of that part of the dome thereby deprived of support. The records are less informative than about the first collapse but it is recorded that more than a century before the western arch fell it was already seriously cracked and some repair was undertaken and that the third collapse, like the first, occurred not during an earthquake but some time later - on this occasion a year and a half later. Both reconstructions were limited to the replacement of what had fallen, leaving largely untouched to this day the 6th century sections of the dome that had remained standing. Reconstruction of the eastern arch, the upper part of the eastern semidome, and the adjacent parts of the eastern pendentives seems to have been intended simply to reinstate what had fallen, though the work was less precise and there is a particularly clumsy join between the 6th century and 14th century portions of the northern pendentive. Reconstruction at the west was considerably more cautious. There was a significant change in longitudinal profile of the semidome above the level of the windows (Fig.1), a considerable increase in depth and width of the reconstructed part of the arch (Fig.2), and several additions including the blocking of two windows at each end of the dome reconstruction (Fig.4).
The further major reconstruction that is not explicitly recorded was of the great tympana - the window-filled walls set within the main north and south arches. The original large upper window in each was replaced by a number of smaller ones and, thanks to the reconstruction, the tympana were relieved of load from the earlier settlement of the arch crowns and are now much less extensively cracked than they would otherwise be.

More significant than this reconstruction from the point of view of the present safety of the whole structure are some of the numerous additions, repairs and consolidations undertaken from a fairly early date. They include virtually all the buttressing masses (other than the corner access ramps) that now surround the exterior up to gallery roof level and numerous iron ties and cramps and infillings of both stone and brick (Figs 1 and 4).

Figure 4 Exploded isometric plans at ground and gallery and at the bases of the semidomes and dome, showing infills and added ties inset at floor level. Brick infills are shown by vertical hatching, stone infills by horizontal hatching, and ties by heavy broken line. Light and heavy stippling denote respectively 6th century and later reconstructions. (Author)
The earlier buttressing masses are not solid but contain stairs, chapels and other rooms. The later ones range from the gothic-looking (but probably much earlier) flying buttresses at the west to the more substantial ramped masses and fliers against the north, south and east sides. There are also four Ottoman minarets standing on substantial bases at the corners.

Most of the infillings are to be found in the buttress piers across the aisles from the main piers. These were constructed for most of their height in brick and initially had large voids serving as entrances or to accommodate stairs. More important probably are the infillings to the main piers at gallery level, made in at least two stages to bring their cross section closer to those above and below. They are not identical in all piers: the north-south tunnel vault in the main north west pier is still unfilled whereas all its counterparts were filled, probably in the 16th century. There are also numerous fillings of windows and of previous voids in the dome base.

The total number of added ties and cramps is unknown. A few only, set into the gallery floor, are shown in Fig.4. There are others conspicuously spanning between column heads or across the springings of vaults in both aisles and galleries. And it is known that circumferential ties were set around the base of the dome in 1848 and again in 1926. But no sign has been seen of ties also envisaged in 1848 between the springings of the main north and south arches.

The intention behind these works is rarely stated as being more than to make good the ravages of time and neglect or to forestall a supposed impending collapse. But in most cases it was clearly to halt outward movements, either of the primary structure or of the secondary structure of the aisle and gallery vaults. Both ties and buttresses were used for this purpose. The infills to the buttress piers and other associated additions and reconstructions may well have had the same objective. But the infills to the main piers at gallery level were more likely intended as underpinning to reduce the vertical load on their original cross sections when splitting of the masonry suggested dangerous overloading. Restraint of a feared splitting away of one 6th century projection from the main body of the south-west pier was clearly the intended purpose of long horizontal cramps that were exposed in the 1930s on its east face.

PRESENT STATE

Together these works have left the structure an even more complex one than it was when first completed in 537. But, since the investigations on which the above account is based were conducted primarily to learn more about the church in the 6th century, many details relevant to present safety remain unexplored.

Doubts remain about foundation conditions and about internal
details of the main structure and some additions. Nothing is known, for instance, about the interior of many of the outer buttresses or about the precise locations and present strengths of the dome ties. And, while many unbonded joints and voids—some filled or partly filled—have been identified, not all have been explored and there are probably others as yet unknown.

As for the present state of the masonry, the broad pattern of cracking in the primary structure can be inferred from proven deformations that are far in excess of possible elastic and early plastic ones. Though most cracks depicted in Fig.5 were hidden when investigation started and remain largely hidden today, this pattern has been checked by limited uncovering now recorded in the survey drawings\(^1\), and it does indicate the most important features of the present transmission of outward thrusts. But while earlier exposures of the masonry of the southern main piers at gallery level revealed instances of the splitting referred to above under the high local compressions due to a reduced cross section and imperfect bearing between blocks, the full present state of these piers and their northern counterparts is not known. Nor is the present condition of those regions of the main transverse arches where high local compressions are also to be expected as a result of hinging deformations.

PRESENT SAFETY AND CONSERVATION FOR THE FUTURE

Because of these uncertainties and the impossibility of direct measurement of relevant material properties, a quantitative assessment of safety such as is now made when designing a new structure is not feasible even under static loading, and still less under dynamic loading in the absence of a relevant proven theory. Nor can useful guidance be obtained from inverse analysis of arbitrarily simplified models drawing on what has already been deduced about the growth of deformations and on such low-amplitude dynamic characteristics as can now be measured. Such analysis cannot discriminate between models that would be valid for predicting future behaviour and others that could be misleadingly invalid.\(^5\)

It is therefore necessary to rely more directly on what the structure has disclosed by its behaviour hitherto.

The cracking of the vaults is not, in itself, a major cause for concern. The masonry dome, for instance, is an inherently stable form even when cracking extending upwards from windows around its base reduces it to a ring of arches with a common keystone in the uncracked crown region. With a thickness of 5% or more of the radius of curvature, collapse can occur only if there are large outward movements at the base or local failures under the radial compressions. There is a risk of the latter if water seepage over a long period seriously weakens the mortar, as does appear to have happened in 1824 in one of the minor domes over the galleries. But not otherwise. Much the same is true
Figure 5a (above) Thrust lines (arrowed) and circumferential compressions (full line) in the main vaults and the general pattern of associated cracking (broken line) at successive stages of construction. "S" denotes a major shear failure above the level of the gallery floor. (Author)

Figure 5b (left) A detail of one of the shear failures. It is shown above the gallery roof in the position indicated by the heavy line lettered "a" in the upper drawing. The barrel vault shown in section through its crown and stippled is a late reconstruction. The dome is to the right, the buttress pier to the left. (Author)
for the semidomes, abutted as they are at their boundaries.

Cracking in the structure as a whole even has one beneficial effect. As amplitudes increase during an earthquake it leads to reductions in natural frequencies which make damaging resonance with a predominant ground motion highly unlikely. This may be why Hagia Sophia came through the 1766 earthquake unscathed while the Suleymaniye Mosque, closely modelled on it but without the weaknesses noted above and completed only two centuries earlier, did suffer damage to its high vaults.6

The main cause for concern is continued growth of the cracks in the main support system. Slow growth results from repeated slight opening and closing of the cracks to accommodate thermal strains and from their progressive jamming further and further open by intrusive debris. Earthquakes hasten this process. Indeed this is probably the chief mechanism whereby they damage a masonry structure that is already extensively cracked in finding its own equilibrium state.

Further splitting of the masonry of the reduced sections of the main piers at gallery level could eventually result in sudden

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Figure 6 Average north-south inclinations of the upper stages of the four main piers expressed as percentages of the present average inclination. The width of the band indicates roughly the margin of uncertainty (Author)
failure under purely vertical load. The fillings and other additions shown in Fig. 3 should, however, have led to some net increase in safety over the past few centuries.

The chief risk seems, therefore, to stem from the increases in the transverse inclination of the piers that result from the crack growth. Previous collapses of the east and west arches occurred through excessive outward movements of their springings and excessive local compressions at the hinge regions at crown and haunches. Further movements could lead in the same way to further collapses.

The study of inclinations up to the present (Fig. 6) does suggest a continuing movement, though the recent history was merely interpolated and no distinction was made between slow long-term increases and the rapid increases during earthquakes. A possible interpretation is a fairly uniform increase since the 6th century of about 1% of the present inclination every 80 years plus rapid growths of up to 3% during earthquakes. But the recent tying of the dome base and the fact that even the newer peripheral buttresses should now be providing fully effective support suggest that the present actual and potential rates of increase should be substantially lower.

The further increase possible without another collapse depends partly on the known geometry of the arches and partly on the largely unknown strengths in the critical crown and haunch regions already referred to. Taking into account the greatly increased cross section of the rebuilt part of the western arch and all other relevant factors, there should be no immediate danger. Indeed, since the much greater sections and lesser spans of the north and south arches make them much less vulnerable, it might be concluded that the whole structure, strengthened as it now is by added ties, buttresses and infills, will stand for many more years if there is no great deterioration of its materials.

To confirm this assessment, the chief need now seems to be some examination of the critical regions coupled with monitoring of critical spans and separations at cracks over a long enough period to allow cyclic movements to be discounted. Recording of strong-motion dynamic responses to indicate actual modes of response outside the elastic range would also be helpful.

If sufficient confirmation of present safety is not thereby obtained, making some precautionary intervention advisable, the aim should be to enhance safety without loss to the original structure or to the character of the present dynamic response. Measures meeting these criteria would be the consolidation (if inspection suggests that it is desirable) of some of the present infills and the renewal or supplementing of some of the present ties. Statical calculation, using models based on the observed modes of deformation, would be feasible and essential here to determine appropriate tie forces.
Whatever else is done, there is a continuing need for proper maintenance of the external weather shield, especially the lead covering of the vaults, and for the making good of any seriously weakened mortar. In the past this essential maintenance has been too much neglected. This neglect is referred to in the records even more frequently than earthquakes as the cause of damage. Even in recent years it has been too common to see figs and other vegetation growing through holes in the lead. A worse state is described in early 19th century accounts and shown in photographs taken early in this century. It must not be allowed in the future. About this there can be no question.

REFERENCES


2 The most relevant precedents are discussed in Mainstone, 1988, chapter 7. The church of St Polyeuctos has been claimed as a more complete forerunner by its excavator in Harrison, M, A temple for Byzantium, Harvey Miller, London 1989. But no fallen dome masonry was found to support this claim, the suggested reconstruction poses far more problems than it solves, and other reconstructions seem more consistent with the evidence.


4 Mainstone, 1988, plate 238, shows the Holy Trinity, Budva.

5 Modelling possibilities are discussed further in Mainstone, 1992.

6 Sinan's Suleymaniye Mosque is the most direct subsequent response to the challenge posed by Hagia Sophia and might almost be described as Hagia Sophia through Sinan's eyes. Freed of some of the constraints under which Justinian's architects worked, Sinan produced a structurally more logical design with stronger interconnections between main and buttress piers and a greater use of cut stone and iron ties. See Mainstone, R J, "The Suleymaniye Mosque and Hagia Sophia", IASS Symposium on public assembly structures, Mimar Sinan University, Istanbul, 1993 (in the press).

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